FINAL TECHNICAL REPORT FOR NASA GRANT NAGW-3268
"THE UNITY OF ACTIVITY IN GALAXIES"

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1) Ionized Gas in Active Galaxies

a) Extended High Excitation Gas Studied in Optical Emission Lines

A long term program on ionized gas in active galaxies using ground-based optical telescopes and HST has continued.

i) A Survey of Seyfert Galaxies and Implications for Unified Schemes

Mulchaey, Wilson & Tsvetanov (1996a) have published the first emission-line imaging survey of a complete sample of Seyfert galaxies. Flux-calibrated images in the lines of [OIII]λ5007 and Hα+[NII]$\lambda\lambda$6548,6583 and the nearby continuum are presented for 57 Seyfert galaxies of early morphological type. This sample includes all known Seyferts with apparent magnitude $m_V \leq 14.5$ and recessional velocity $cz < 7000$ km s^{-1} in Hubble types E, S0 and S0/a. Images are also presented for an additional 26 galaxies with $m_V > 14.5$, $cz > 7000$ km s^{-1}, and/or an uncertain classification as a Seyfert galaxy. The ratio of the [OIII]λ5007 to the Hα+[NII] image has been obtained for each galaxy with extended emission to study the spatial variation of the gaseous excitation. Maps of the V-R color distributions over the galaxies are also presented.

In Mulchaey & Wilson (1995), the emission-line and optical continuum axes in a sample of 29 of the Seyferts in the above imaging survey are compared. We find a strong trend for the continuum to align with the [OIII]λ5007-emitting gas on a scale of several arc-seconds (hundreds of parsecs). This trend is observed for both Seyfert types. There is no alignment, however, between the small scale emission-line axis and the overall orientation of the host galaxy. We investigate several explanations for the alignment of the [OIII]λ5007 emission with the continuum on small scales, including the possibility that the non-stellar continuum is extended in Seyfert galaxies. An extended non-stellar continuum component in Seyferts might solve several outstanding problems in currently popu lar unified models.

In Mulchaey, Wilson & Tsvetanov (1996b), the implications of the imaging survey for unified models of active galaxies are evaluated. In unified models, the active nucleus is surrounded by a thick, dusty gaseous to rus. The nuclear ionizing radiation is then expected to escape in oppositely directed cones along the axis of the torus. We have, therefore, performed simulations in which ambient gas is ionized by a bi-conical radiation field. When the ambient gas is distributed in a sphere or spheroid, V-shaped projections are expected whenever our line of sight is outside the cones of ionizing radiation. For line of sights within the cones, "halo" -like morphologies are produced. For such gas distributions, the measured opening angle of the V-shaped morphology is equal to or larger than the true opening angle of the radiation field. On the other hand, when the gas is distributed in a thin disk, V-shaped projections are produced most of the time, even when our line of sight is within the photon cone. The measured opening angle in this case is usually smaller than the true opening angle of the photon cone. For both spherical and thin disk gas distributions, the projected linear extent of the ionized gas tends to be smaller for lines of sight within the cones.

From the emission-line images, we find that extended emission line gas is very common in Seyfert galaxies, with $\sim$ 80% of the galaxies showing extension in our [OII I]λ5007 images and $\sim$ 100% showing extension in Hα + [NII]. The percentage of galaxies extended in these lines is comparable for Seyfert 1's and 2's. There is a strong correlation between the line fluxes of the unresolved core and the extended emission, suggesting the extended emission is ionized by the same source that ionizes the nuclear gas. There is also a correlation between emission-line extent and luminosity.

In order to evaluate the unified model, the simulations and observations are compared. The

total [OIII]λ5007 luminosities of the Seyfert 1's in our sample are similar to those of the Seyfert 2's, while the total Hα+[NII] emission is larger in Seyfert 1's than Seyfert 2's. This result is not surprising since the broad component to the Hα line contributes a significant amount of flux in the Seyfert 1's. In order to compare the extended emission-line luminosity of the two Seyfert types, we have subtract ed an unresolved nuclear component from the images. We find a trend for the extended emission in both [OIII]λ5007 and Hα + [NII] to be more luminous in the Seyfert 1's than the Seyfert 2's. However, this trend is of only marginal significance in the complete sample.

In general, it is difficult, if not impossible, to distinguish a Seyfert 1 galaxy from a Seyfert 2 galaxy based only on its emission-line characteristics. While linear, bi-polar or V-shaped morphologies are seen in some objects, for one-third of the sample the emission-line structures are 'halo'-like. These 'halo' morphologies are not expected for Seyfert 2's in the unified model. Many of the 'halo' Seyfert 2's do display linear or V-shaped structures in their excitation maps i.e. distributions of [OIII]/Hα+[NII]), so they may still be consistent with orientation-dependent models. However, the emission-line morphologies of at least a few Seyfert 1's appear inconsistent with those expected in the simplest unified schemes. In our complete sample, the extent of the [OIII]λ5007 emission at a given surface brightness is larger in the Seyfert 2's than the Seyfert 1's. However, this difference disappears if the two most extended Seyfert 2's are omitted.

We also find evidence for structure in many of the continuum color maps. In $\sim$40% of the galaxies with color maps, red (V-R $>$ 1.0) features are found. The majority of these red regions are unresolved structures located at the nucleus. These features are found in galaxies of all inclinations, but occur almost exclusively in type 2 Seyferts. These characteristics are consistent with reddening by $\sim$ 100 pc-scale, dusty tori. A less likely alternative is that these structures represent a very red stellar population (later than K5). Diffuse blue (V-R $<$ 0.5) features are seen in some Seyfert 2 galaxies. These blue excesses tend to be spatially coincident with the high excitation gas, suggesting an origin related to the nuclear activity. The blue excesses could originate from a number of different processses, including scattered nuclear light or an extended non-stellar continuum associated with the ionized gas (e.g. shock waves).

ii) Ionization and Excitation of the Gas

There is currently a controversy concerning the source of ionization of the extended gas seen in active galaxies. In one picture, the gas is photoionized by a compact nuclear uv-X-ray source. In the other, high velocity shocks within the extended gas provide the ionization, much through photoionization by radiation emitted by the shocks ("photoionizing shocks"). There are some differences in the predictions of the two models in the strengths of certain lines. For example, the mean temperature in the shock models is expected to be higher, and so [OIII]4363 and collisionally excited uv lines should be enhanced.

Unfortunately existing high quality spectra of active galaxies are mainly restricted to the nuclei, where densities in excess of 10^6 cm^{-3} may be present and compromise the use of [OIII]4363 as a temperature diagnostic. Storchi-Bergmann et al. (199b) have therefore obtained long-slit spectroscopy of five Seyfert galaxies and radio galaxies showing extended high excitation emission lines reaching distances of several kiloparsecs from the nuclei. Measurement of the fluxes of weak lines, such as [OIII]λ4363 and HeIIλ4686, requires careful subtraction of the contribution of the stellar population, and the procedure for this subtraction is discussed in detail. In the companion paper (Binette, Wilson & Storchi-Bergmann 1996), these line ratios are used to discriminate between different types of photoionization models. A well known problem, the scatter and the extreme values of He II/Hβ encountered in the nuclei and extended regions, is solved in a similar fashion to Viegas & Prieto (1992) by considering two populations of ionized clouds: a matter-bounded (MB) component responsible for most of the He II emission, and an ionization-bounded (IB) component emitting low-to-intermediate excitation lines. A new sequence of photoionization calculations is thereby obtained by varying $A_{M/I}$, which is defined as the solid angle ratio occupied by the MB component relative to the IB component. In various line ratio diagrams, the $A_{M/I}$–sequence is compared to the traditional single component U–sequence in which one arbitrarily varies the relative intensity of the ionizing source. An original aspect of the new calculations is that the IB

clouds are photoionized exclusively by the radiation which has filtered ('leaked') through the MB component. This situation could arise if, for example, the MB component is the low density 'halo' of a cloud, and the IB component the high density core. Such a filtered ionizing spectrum enlarges the range in He II/Hβ accessible to models without requiring changes in the spectral index of the ionizing source, which we fix at α=3D−1.3. The main success of the model is that it provides a natural explanation for the newly found correlations between both the [O II]/[Ne V] and [OII]/[O III] ratio and the He II/Hβ ratio. On the other hand, the standard U–sequence cannot account for such correlations between the gaseous excitation and the He II/Hβ ratio. Furthermore, the so-called 'temperature problem' is solved with the $A_{M/I}$–sequence provided the thickness and the ionization parameter ($U_{MB} \geq 0.04$) of the MB component are appropriately selected. Finally, the $A_{M/I}$–sequence produces much stronger high excitation lines of [Ne V] and C IV$\lambda\lambda$1549 than the U–sequence, in accordance with observations. The $A_{M/I}$–sequence predicts a temperature difference of 5,000K between the T_{OIII} and T_{NII} temperatures while for the U–sequence this difference is less than 1,000K. To the extent that 'cooling flows' and LINERs share the same excitation mechanism as our IB component (i.e. photoionization by an absorbed ionizing continuum), we predict a value of He II/Hβ<0.01 while the U–sequence is charaterized by a value >0.1. Our conclusion is that all line ratios can be accounted for in "pure" photoionization models, without the need for shocks.

Morse, Wilson & Raymond (1996) have presented a critique of the photoionizing shocks model for ionized gas in active galaxies by referring to observational evidence for photoionizing shocks in nearby objects. Photoionizing shocks are observed in Herbig-Haro objects and supernova remnants (SNRs), where there are no strong, external sources of ionizing radiation, removing the ambiguities that persist in the regions surrounding active galactic nuclei. We show that in one SNR, the radiation field produced behind fast shocks is found to photoionize the precursor gas and generate a Seyfert-like spectrum. We conclude that photoionizing shocks are a viable mechanism for generating the emission-line spectra observed in the narrow line regions in active galaxies, but only under those circumstances where shocks are likely to be formed, e.g., through the interaction of a radio jet with the ISM. In those objects where sharp, straight-edged ionization cones are observed, beamed ionizing radiation from the active nucleus is preferred over photoionizing shocks. We show, however, that photoionizing shocks may help to resolve the UV photon deficit problem in some objects because a significant fraction of the ionizing radiation is emitted as line emission in the EUV. In fact, the UV continuum flux near 1300Å from a 400 km s^{-1} shock is $\sim$ 100 times lower than that from a power law containing the same number of ionizing photons. We discuss the implications of the strengths of collisionally excited UV lines, the weakness of Ca II lines, and the high electron temperatures derived from the [O III](λ4959 + λ5007)/λ4363 ratio for the ionization mechan ism. The observed extended soft X-ray emission in nearby AGNs may originate in shock-heated gas.

iii) Ionization Cones

Ionization Cones are V-shaped emission-line regions with apex at the active nucleus. They are presumed ionized by a collimated nuclear radiation source.

Wilson & Tsvetanov (1994) have obtained radio maps at three frequencies of the Seyfert 2 galaxy NGC 5252, which is known to exhibit a spectacular pair of "ionization cones" in optical emission-line images. The radio structure of the galaxy comprises an unresolved (< 50 pc) source coincident with the optical nucleus, weak, narrow features extending $\simeq$ 900 pc to north and south from the nucleus, and an unresolved radio source some 10 kpc from the nucleus. The inner parts of the extended radio structure and the off-nuclear source align well with the axis of the ionization cones. There are currently 11 Seyfert galaxies known to possess an ionization cone or a bi-cone; 8 of these galaxies also contain a linear (double, triple or jet-like) nuclear radio structure. For this limited, incomplete sample, there is a tight alignment between cone and radio axes: the formal mean difference between the measured projections of these axes on the sky is only 6°, and the alignment may well be better than this at the location(s) closer to the nucleus where the collimation occurs. Although the *degree* of collimation is much worse for the ionizing photons than for the radio plasma, it is clear that they are collimated by the same, or coplanar, nuclear disks or tori. In particular,

if the ionization cones result from absorption by dusty tori on the pc scale and the radio ejecta from accretion disks around the central black hole, the absence of differential precession indicates that either the gravitating mass distribution is close to spherical or the dusty torus has settled into Ga preferred plane. The cones currently known in late-type (but not early-type) spirals show a trend to align with the axis of the galaxy stellar disk. We argue that this alignment is either an observational selection effect or indicates that the gas accreted to power the nuclear activity has an internal origin in late-type spirals, but may have an external origin (e.g. a galaxy merger) in early-types.

Wilson et al. (1993) have reported high resolution (0.1″) observations of the Seyfert 2 galaxy NGC 5728 with the Hubble Space Telescope. Images have been obtained in the light of [OIII]$\lambda\lambda$4959,5007, Hα + [NII]$\lambda\lambda$6548,6583 and green and red continua. The emission-line images reveal a spectacular bi-conical structure with overall extent 1.8 kpc. The two cones share a common axis and apex. The cones' axis coincides to within $\simeq 3°$ with that of the one-sided nuclear radio continuum emission but is not aligned with the rotation axis of the galaxy disk. No [OIII] and only weak Hα + [NII] emissions are seen at the apex itself, where the continuum is also weak and its color red. These results suggest our line of sight to the cones' apex is obscured or blocked. The apex almost certainly reflects the location of the "true" active nucleus, for it coincides with the radio nucleus, the gaseous kinematical center, and the geometrical center of the circumnuclear star-forming ring (which has been interpreted in terms of an inner Lindblad resonance). Bright, bar-like features are seen in continuum light and may represent either a kpc-scale stellar bar or scattered nuclear light. Our data provide strong support for unified models of Seyfert galaxies, in which Seyfert 2 nuclei are blocked from direct view by an optically thick torus or other structure, with optical and ultraviolet radiation escaping preferentially along and around the torus axis.

iv) Interactions between Radio Jets/Lobes and Gas in the Narrow Line Region

Our HST imaging observations have revealed strong associations between radio jets and lobes and resolved ionized gas. Such associations are found in NGC 5929 (Bower et al. 1994), Mulchaey et al. (1994) and Mkn 1066 (Bower at al. 1995). This association can be in the form of gas surrounding radio lobes (NGC 5929) or jet-like emission-line features associated with the radio jets (NGC 2110 and Mkn 1066). It is believed that the outwardly moving radio ejecta shock and compress ambient gas. This gas is then ionized by photons from the nucleus or from the shocks themselves. The referenced papers may be consulted for details on individual objects.

v) Other Results

Tsvetanov et al. (1996) have obtained HST several *HST* WFPC2 emission-line and continuum images of NGC 5252, a Seyfert 2 S0 galaxy with a large-scale "ionization bi-cone". In the Hα+[N II] image the nucleus is bracketed at ~0.3 arcsec radii by two bright emission-line clumps along PA 35° (~20° from the major axis of the large-scale stellar disk.) These three knots dominate the emission in the innermost ~ 1 arcsec (~450 pc at 92 Mpc distance). Two major and several smaller spiral filaments, wound tightly counter-clockwise, extend ~3 arcsec to the NW and ~4.5 arcsec to the SE of the nucleus. Several of these filaments extend from the two clumps near the nucleus, possibly indicating that the three collinear knots comprise a bar. Our Fabry-Perot velocity map shows that the spiral pattern is rotating, in a disk inclined significantly to both the galaxy stellar disk and the radio jets. The nuclear radio jets appear to have no obvious association with the Hα+[N II] filaments and clumps. Although most of the line flux is emitted within the inward extrapolation of the large-scale ionization bi-cone, some of the Hα+[N II] filaments extend beyond the cone boundaries. A remarkable "D"-shaped pattern of obscuring dust is visible on the NW side of the galaxy major axis. Most of the spiral filaments in the Hα+[N II] image also appear in the obscuration map. The extinction by the filaments requires a column density of $N_H \approx 5 \times 10^{20}$ cm^{-2}. If the filaments are uniformly filled, both the gas responsible for the extinction and the ionized gas responsible for the emission have number densities of a few cm^{-3}.

Bower & Wilson (1995) have published HST images of the spiral galaxy NGC 5930 in the emission lines [OIII]$\lambda\lambda$4959, 5007 + Hβ Hα + [NII]$\lambda\lambda$6548, 6584. NGC 5930 is the interacting companion of the Seyfert 2 galaxy NGC 5929. A ring of continuum knots and low excitation ionized

gas is found in the central $\simeq$1.5 arcsec (200 pc). This nuclear star forming ring appears to be similar to other nuclear rings in spiral galaxies which may form at or near the inner Lindblad resonance. If this is the case for NGC 5930, the small radius of the ring implies a strongly concentrated central mass distribution.

b) Abundances and Kinematics of Active Galaxies

Storchi-Bergmann et al. (1996b) have investigated the mode of fueling the putative black hole, and the question whether the circumnuclear regions have experienced unusual chemical processing – by studying the kinematics and chemical abundance of the gas in the nuclear region of galaxies with sites of on-going star formation near the active nucleus. Results are presented for three galaxies with nuclear rings. The two galaxies with LINER nuclei appear to have two Inner Lindblad Resonances, with the star-forming rings located between them. The high S/N ratio of the data has allowed us to detect faint ionized gas – a warm ionized medium – up to several kpc from the nuclei. We find a correlation between the [NII]/Hα and [SII]/Hα ratios and the FWHM of the [NII]λ6584 emission-line. This correlation is strongest for the circumnuclear gas, but is also present in the warm ionized medium, and is interpreted as a result of shock ionization. We have also obtained the chemical composition of the HII regions in the ring and far beyond. The highest central metallicities (O/H$\approx$ two times solar and N/O $\approx$ three times solar) were found around the two LINER nuclei, confirming previous results based on spectroscopy of the narrow-line region that LINER nuclei have abundances considerably in excess of solar. Nevertheless, these abundances are similar to those of the nuclei of non-active galaxies with the same morphological type and absolute magnitude.

c) Double-Peaked Broad Lines in Active Galaxies

In 1991, we discovered the sudden appearance of very broad ($\approx$ 20,000 km s^{-1}) Balmer recombination line emission from the LINER nucleus of the galaxy NGC 1097, a galaxy which had previously shown only narrow line emission. Such line profiles are commonly thought to be indicative of a rapidly rotating disk or high-velocity bi-polar outflow and are thus of great relevance to the AGN paradigm. NGC 1097 represents the first time such a double-peaked line had appeared when none was previously seen and the first example in a radio-quiet AGN. Since 1991, we have monitored variations in the Balmer profiles (Storchi-Bergmann et al. 1995). Between 1991 and 1994, the integrated Hα flux has decreased by a factor of 2, the Hα/Hβ ratio has increased, and the originally asymmetric Hα profile has become symmetric. The decline of the Hα flux and the change in the Hα/Hβ ratio can be interpreted as consequences of either increased obscuration along the line of sight, or a decline in the ionizing continuum, but neither of these scenarios can account for the change in profile shapes. A model attributing the line emission to a precessing elliptical ring around a 10^6 solar mass nuclear black hole can reproduce the observed profile variations. In this scenario, the line-emitting ring is the result of the tidal disruption of a star by the black hole. Alternative scenarios associating the broad line emission with a collimated bipolar outflow also remain viable, but binary black holes and inhomogeneous accretion disks are disfavored by the observed pattern of variability.

d) Hot Gas Studied in X-ray Emission

A program of imaging of nearby Seyfert galaxies with the High Resolution Imager on the ROSAT X-ray satellite has continued. Results were published for several galaxies, with those for NGC 2110 being combined with observations with NASA's Broad-Band X-ray Telescope (Weaver et al. 1995). A spectacular image was obtained for NGC 4258, with the long radio and emission-line jet standing out prominently in X-rays (Cecil, Wilson & De Pree 1995). In NGC 4151, the extended X-ray emission is associated with the extended narrow line region (Morse et al. 1995). To date, extended X-ray emission has been found around the nuclei of 5 Seyfert galaxies. The extended emission is typically $\approx$ kpc in spatial extent, has luminosity $\approx 10^{40-42}$ erg s^{-1} and aligns with the radio and/or ENLR axis. The extent of the X-ray emission is very similar to that of the extended optical line emitting gas. If the extended X-rays are interpreted as thermal emission, the pressure of the hot gas is similar to that of both the gas at 10^4K and the radio synchrotron

emitting electrons plus magnetic field. The hot gas may be associated with an outflowing wind or may represent gas entrained and shocked by the radio ejecta or jets. This work has been summarised by Wilson (1994) and in a paper at the Würzburg conference " Röntgenstrahlung from the Universe" in September 1995.

2) Dusty Tori in Active Galaxies and Unified Models

Mulchaey et al. (1994) have used multi-wavelength data on Seyfert galaxies to try to distinguish between isotropic and anisotropic emissions. The distributions of [OIII]λ5007, infrared, and hard X-ray continuum are similar for Seyfert 1's and Seyfert 2's, consistent with these properties being isotropic. The ultraviolet and soft X-ray continua of Seyfert 2's are underluminous relative to the type 1's suggesting photons at these energies escape from the central source anisotropically. There is a correlation between the ultraviolet continuum and emission-line fluxes in Seyfert 1's consistent with the idea that the central source is responsible for powering the line emission. No such correlation is found for Seyfert 2's. Instead, the scatter in the plot of ultraviolet continuum versus line emission suggests the true nuclear continuum luminosity is not seen at Earth in these objects. These properties are consistent with those expected in the dusty torus model.

Simpson et al. (1995) have obtained optical and near-infrared imaging and spectroscopy of the giant radio galaxy PKS 0634-205. The images longward of 2 μm reveal the presence of an extremely red compact source coincident with the nucleus, which is not detected at shorter wavelengths. The observed $K - L$ color of this source, the [OIII] flux and the soft X-ray flux are consistent with the spectral energy distribution of a typical quasar observed through a visual extinction $A_V \sim 30$ magnitudes. Our 2 μm spectrum shows strong narrow Paα, but has insufficient sensitivity and wavelength coverage to reveal broad Paα from the putative quasar at the predicted level.

Simpson et al. (1996) have reported optical emission-line and near infrared continuum images of the Seyfert 2 galaxy Mkn 348. The optical images reveal a well-defined region of highly ionized gas aligned approximately parrallel to the radio axis, possibly in the form of a bi-cone. In addition, there is a red linear structure in the infrared continuum, oriented perpendicular to this axis and approximately 1 kpc in extent. We examine the possibility that this latter structure is emission from hot ($\approx$ 900K) dust in a disk or torus viewed approximately edge-on. The disk may comprise the outer parts of the dusty torus postulated in schemes to unify the two types of Seyfert galaxy. The featureless continuum may come from hot stars associated with a 4 kpc diameter ring of HII regions surrounding the nucleus.

3) The Origin of Radio Galaxies

The recent development of unified theories of active galactic nuclei (AGN) has indicated that there are two physically distinct classes of these objects - radio-loud and radio-quiet. The primary observational distinctions between the two types are: (1) The radio-loud objects produce large scale radio jets and lobes, with the kinetic power of the jets being a significant fraction of the total bolometric luminosity. On the other hand, the weak radio ejecta of the radio-quiet objects are energetically insignificant. (2) The radio-loud objects are associated with elliptical galaxies which have undergone recent mergers, while the radio-quiets prefer spiral hosts. (3) The space density of the radio-louds at a given optical luminosity is $\approx$ 10 times lower than that of the radio-quiets. Despite these differences, the (probably) thermal emissions from the AGN (continua and lines from X-ray to infrared wavelengths) are quite similar in the two classes of object. We argue that this last result suggests that the black hole masses and mass accretion rates in the two classes are not greatly different, and that the difference between the classes is associated with the spin of the black hole.

We (Wilson & Colbert 1995) assume that the normal process of accretion through a disk does not lead to rapidly spinning holes, and propose instead that galaxies (e.g. spirals) which have not suffered a recent major merger event contain non-rotating or only slowly rotating black holes. When two such galaxies merge, the two black holes are known to form a binary and we assume that they eventually coalesce. In the small fraction of mergers in which the two "parent" galaxies contain very massive holes of roughly equal mass, a rapidly spinning, very massive hole results.

It is proposed that such mergers are the progenitors of powerful radio sources, in which the radio jets are powered by the spin energy of the merged hole. We calculate the distributions of mass and spin for the merged holes from the parent hole mass distribution, which is derived from the optical luminosity function of radio-quiet AGN adopting different activity patterns. The ratio of the number of radio-loud to radio-quiet AGN's at a given thermal (e.g. optical) luminosity is determined by the galaxy merger rate. The required fraction of galaxies which merge during the average lifetime ($\approx 10^8$ yrs) of a radio-loud AGN is found to be 10^{-1}, i.e. a merger rate of 1 in $\simeq 10^9$ yrs. The Blandford-Znajek formalism is then used to predict the radio luminosity and radio luminosity function of the merged population. Comparisons between the predicted and observed radio luminosity functions constrain the efficiencies with which jet power is extracted from the spinning hole and radio emission is produced by the jet. The cosmological evolution of the radio properties of the radio-loud objects is related to the increased frequency of merger events at earlier epochs.

4) Water Vapor Megamasers in Active Galaxies

In collaboration with Jim Braatz (graduate student, UMd) and Christian Henkel (MPIfR, Bonn), work has continued on H_2O megamasers in active galaxies. H_2O masers are of particular interest in AGN studies because they are believed to originate in very dense gas ($\approx 10^{10}$ cm^{-3}) and, in at least one case, the gas is in a Keplerian rotating disk at about 0.1 pc from the putative black hole. When we began this project in 1993, only 5 examples of H_2O maser emission from active galaxies was known. Our initial survey immediately doubled this number (Braatz et al. 1994), including detection of the most distant known water in the Universe, which led to widespread publicity in the popular media (Braatz has been invited to give a press release on this work at three separate meetings of the American Astronomical Society over the last 2 years). At present, we have discovered 10 new megamasers. Recently, the emphasis has been on completing a survey of a complete sample of some 350 active galaxies (Braatz et al. 1996) and investigating the statistical properties of this sample, monitoring the time variability of the masers, determining their arc sec scale spatial structure with the VLA and initiating VLBI studies to map them on the milliarcsecond scale.

For one galaxy (NGC 2639), the brightest maser feature has drifted systematically towards higher recessional velocity. This situation is reminiscent of that in NGC 4258, where the systemic maser features result from emission at the near side of a Keplerian disk and the redward drift is simply the centripetal acceleration of orbiting gas clouds. Knowledge of the centripetal acceleration allows a combination of the black hole mass and disk radius to be determined (Wilson et al. 1995).

All megamasers are in Seyfert 2's or LINERs's, and none in Seyfert 1's, consistent with the requirement of an edge-on viewed disk, as is known to be the case in NGC 4258. There is also a trend for the galaxy disks of the known megamasers to be preferentially edge-on. A very extensive study of the relation of the maser properties to the other known properties of the galaxies in the sample of 350 is nearing completion.

5) An IUE Study of the nature of the featureless continuum in Seyfert 2 galaxies

Type 2 Seyfert nuclei are well-known to contain a 'featureless continuum' which makes a significant contribution in the optical and ultraviolet. However, the nature of this featureless continuum is not clear. Recent optical spectrophotometry shows that only a minor part of the optical featureless continuum can be light from a hidden Seyfert 1 nucleus scattered into our line-of-sight. In our study (Heckman et al. 1995), we show that this is also true in the ultraviolet.

We have used IUE spectra of 20 of the brightest type 2 Seyfert nuclei to construct a spectral template of a type 2 Seyfert galaxy. While the continuum is well detected in the template, there is no detectable broad line region (BLR). Comparing this template to a similar spectral template of type 1 Seyferts implies that no more than 20% of the Seyfert 2 template's continuum can be light from a hidden Seyfert 1 nucleus scattered by dust or warm electrons. If the scatterers are very hot electrons (T > few $\times$ 10^7K), the BLR emission-lines can be broadened beyond recognition in our data. However, a scatterer this hot is inconsistent with optical spectropolarimetry. Free-free

emission from the type of warm mirror seen in NGC 1068 cannot produce the ultraviolet continuum because the equivalent widths of Lyα and HeIIλ1640 are an order of magnitude too small in the Seyfert 2 template.

Thus we suggest that the ultraviolet continuum in these Seyfert 2's is primarily produced by a reddened starburst: a circumnuclear population of massive stars which is unusually luminous in type 2 Seyferts compared to normal galaxies of the same Hubble type. We show that our Seyfert 2 template is consistent with existing IUE spectra of metal-rich starbursts in all its salient properties. One consequence of this would be that much of the far-infrared emission detected from these Seyfert 2 galaxies must be powered by the starburst. Althought the type 2 Seyfert template is not of adequate quality to allow the direct spectroscopic detection of massive stars, this should be possible in the near future with HST.

6) Studies of Herbig-Haro objects and supernova remnants

Morse, Hartigan, Raymond and collaborators continued to study the kinematics of protostellar jets, with special emphasis on entrainment processes that transfer momentum from the jet to the surrounding ISM (e.g. Morse et al. 1994). Shock models were used to estimate mass loss rates in jets. Typical protostellar jets were found to have enough momentum to drive their associated molecular outflows via "prompt entrainment" by shocks along the edges of the flow cavities.

Morse, Winkler, and Kirshner (1995) published Fabry-Perot observations of the young SNR N132D in the LMC that reveal the geometry and expansion rate of the oxygen-rich filaments, presumably the uncontaminated ejecta from the core of the massive progenitor. The ejecta were found to be distributed on the surface of an expanding shell, rather than in an annulus as suggested by previous investigators. Several of the filaments appear to be interacting with dense insterstellar clouds in the vicinity of the exploded star.

7) Patents/Inventions developed under the grant

There were no patents or inventions developed under the grant.

PUBLICATIONS IN REFEREED JOURNALS AND INVITED PAPERS SUPPORTED BY THE GRANT

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